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A review on kiln system modeling

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ABSTRACT

The purpose of this study is to evaluate performance cement of production and cement kiln. The design of energy efficient dryers employing heat pump systems and the dynamic response of the product to the kiln conditions must take into account. In this paper, the formulation of a dynamic and kiln-wide drying model is described. The model predictions have been verified by comparing them with the published experimental data. The model is then used to simulate performance of three industrial kilns. Numerical experiments are carried out to investigate influence of key operating and design parameters on energy consumption of kilns. The model is also used to explore the possibility of manipulating temperature profile within the kiln to reduce energy consumption per tonne of clinker. Cement kiln dust is a fine-grained material produced during the manufacture of cement. At present reuse option is limited and the bulk of cement kiln dust that is not reused in the cement manufacturing process is sent to landfills or stored on-site. Due to the calcium oxide (CaO) content of cement kiln dust, it has the potential to be used as a replacement for lime in treating acidic wastewaters such as acid rock drainage. Slaking of two of the cement kiln dust samples with the highest free lime contents (e.g., 34% and 37% free of CaO) gave elevated pH values statistically comparable to those of the commercial quicklime sample that was characterized as having 87% of CaO. Acid neutralization trials indicate that cement kiln dust samples with low free lime contents could be effective at neutralizing acidic wastewaters.

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1. Introduction

The cement is made of clinker and grinded gypsum and produced from a burned mixture of limestone and clay in certain percentages. A cement kiln is the most vital part of a cement factory whose outcome is cement clinker. Cement is the essential material for civil engineering construction works. Output from the cement industry is directly related to the state the construction business in general and therefore closely tracks the overall economic situation in a region or a country [1,2].

Cement kilns are used for the pyro-processing stage of manufacturing of Portland and other types of hydraulic cements, in which calcium carbonate reacts with silica-bearing minerals to form a mixture of calcium silicates. Over a billion tonnes of cement is made per year and cement kilns are the heart of this production process. Their capacities usually define the capacity of the cement plant. As the main energy-consuming and greenhouse-gas-emitting stage of cement manufacture, improvement of their efficiency has been the central concern of cement manufacturing technology [3].

2. A brief overview on kiln

Portland cement clinker was first made in 1842 in a modified form of the traditional static limekiln. The basic, eggcup shaped limekiln was provided with a conical or beehive shaped extension to increase draught and thus higher temperature needed to make cement clinker. For nearly half a century, this design and minor modifications remained the only method of manufacture. The kiln was restricted in size by the strength of the chunks of raw mixture and if the charge in the kiln collapsed under its own weight, the kiln would be extinguished. For this reason, beehive kilns never made more than 30 tonnes of clinker per batch. To produce a batch of clinker required almost a week: a day to fill the kiln, three days to burn off, two days to cool, and a day to unload. Thus, a beehive kiln would produce a maximum of 1500 tonnes/year [4].

A kiln is basically an industrial oven, and although the term is generic, several quite distinctive designs have been used over the years. The most common one associated with pottery making, both 'Bottle' and their very close relatives 'Beehive' kilns, were also the central feature of any cement works. Early designs tend to be updraft kilns, which were often built as a straight-sided cone into which the flame was introduced at, or below, floor level. At 70 ft, the dome or bottle shape of the kiln, known as the 'hovel', would be quite a prominent landmark. As well as protecting the inner kiln or 'crown', the opening at the top of the hovel also used, to remove the smoke and exhaust gases that were produced during the production process. There was a 3–4 ft gap between the outer wall of the hovel and inner shell of the crown. Due to the fact that the 1 ft thick crown wall would expand and contract during firing, it was reinforced by a number of iron bands, known as 'bonts'. These were set 12 in. apart and ran right around the circular oven. The development of downdraft kilns in the early 20th Century proved to be much more fuel efficient and were designed to force more heated air to circulate around the kiln. The design incorporated a gentle curve at the 'shoulders' of the kiln, which served to reflect the rising heat from the fire at the bottom of the kiln, back down again over the material. The smoke and exhaust was then sucked out through holes at the bottom of the kiln via a flue, which was connected to a nearby chimney. The chimney would also serve a number of neighboring kilns as well. The kiln would be fired for several days to achieve the required temperature to produce cement clinker. Although the above methods were successful, the problem with batch kiln was that it was intermittent and once the product had been produced, the fire was allowed to extinguish and the contents allowed to cool. This not only wasted a lot of heat, but also added to the expense of the finished product [1,5].

In order to save money a kiln was required to run almost continuously, whilst the raw material was somehow fed through it. It was the scenario that leads to the development of the 'Chamber' kiln in the late 1850s. This particular kiln comprised a number of individual chambers which were arranged for the hot flue gases from one chamber to be drawn off to pre-heat the material in the following chambers. Once the first chamber had been filled with raw material, coal was added through the roof holes of the chamber and was then set alight. At the same time, the second chamber was being filled with raw material. The airflow from the first chamber was then adjusted, using a number of dampers, to funnel the hot air through the second chamber to pre-heat the material. More coal was then poured into the second chamber and ignited, as the third chamber was being filled and so on. This process continued along the length of the kiln, so that by the time the last chamber had been fired, the first chamber had already been cleared and re-filled with more raw materials so that the process could continue. Although such chamber kilns were still being installed as late as 1900, the development of the rotary kiln was already started to have a major impact. The rotary kiln was a major advancement for the industry as it provided the continuous production of uniform product in larger quantities.

Around 1885, experiments began on design of continuous kilns. One design was the shaft kiln, similar in design to a blast furnace. Raw mix in the form of lumps and fuel were continuously added at the top, and clinker was continually withdrawn at the bottom. Air was blown through under pressure from the base to combust the fuel. The shaft kiln had a brief period of use before it was eclipsed by the rotary kiln, but it had a limited renaissance from 1970 onward in China and elsewhere, when it was used for small-scale, low-tech plants in rural areas away from transport routes. A typical shaft kiln can produce 100–200 tonnes/day [4,5–7].

3. Kiln model analysis

The kiln model analysis aims to describe tasks and analyses for the calculation of a cement rotary kiln. Procedures involved for this kiln model are [8–11]:

- Structural modeling of the rotary kiln by the finite element method.
- Static nonlinear analysis of a full model.
- Dynamic linear analysis of a full modified model.
- Structural verification, including fatigue and ovalization of the kiln body, according to ASME [12–14] and [15] rules.

In the wet process, kiln feed material is in a slurry form containing 30–40% moisture. It is, therefore, necessary to dry the material in the kiln. There is therefore a drying zone and this part acts as a dryer. To facilitate drying, steel chains are used in the kilns. Depending on the manufacturing process, rotary kilns can be classified into the following types [16]:

- Wet process kilns.
- Semi-dry process kilns.
- Dry process kilns.
- Preheater kilns.
- Pre-calciner kilns.

Due to the wet grinding of the material, the feed is more uniform in composition. Also, dust losses from such kilns are smaller. However, extra fuel is required to dry the feed material.

4. kiln modeling and loading measurement

4.1. Introduction of the physical model

The different chemical, mechanical and thermal requirements of the various sections of the rotary kiln can be distinguished [10,15,17,18]:

- *Inlet part, dry part and preheating part*: High wear-resistant castable or acid bricks, of great porosity and fireproof (refractory) bricks or concrete refractory blocks are used to resistant abrasion. In this part, the entrance ring is subjected to abrasion and in the case of very long rotary kilns a chain zone also supports this stress. In addition, there exist ceramic coatings with a good resistance to thermal stresses.
- *Calcinations part*: In this section of the rotary, kiln which is less affected by chemical and thermal stresses, chamita bricks of different qualities, chemically agglomerated, with 50–60% Al_2O_3 are used.
- *Transition part*: Here extra aluminum bricks with corundum and bauxite on the basis of 50–80% Al_2O_3 are used.
- *Sintering part*: The coating consists exclusively of alkaline-resistant cast able bricks of magnesium MgO–C_2O_3, bricks of chromium–magnesium and pressed dolomite.
- *Outlet and cooling part*: This section is made up of extra aluminum bricks with 65–80% Al_2O_3 and bricks of chromium–magnesium. The outlet ring is composed of bricks with 60% SiC and refractory concrete.

5. Geometry model analyses

The installation components are as follows [7,9,19–21]:

- Rotary kiln shell.
- Kiln tyres.
- Tyre-bearing kiln shell sections.
- Roller stations.
- Drive components.
- Toothed ring and drive pinion.
- Cast steel kiln inlet and outlet segment system.
- Kiln inlet and outlet seals.
- Heating gas generator and burner assembly (Table 1).

Table 1
The main geometrical characteristics of the rotary kiln [22].

Magnitude	Value	Units
Cold real length	124.4	Meters
Inner diameter	4.2	Meters
Number of tyres	5	–
Slope	4	%

Table 2
Thicknesses of the shells along the different sections of the rotary kiln [8,22,23].

Section (mm)	Thickness (mm)	Section (mm)	Thickness (mm)
0–7000	26	67,500–70,500	80
7000–8000	50	70,500–71,500	50
8000–11,000	80	71,500–84,400	30
11,000–12,000	50	84,400–94,000	40
12,000–36,500	26	94,000–95,000	50
36,500–37,500	50	95,000–98,000	80
37,500–40,500	80	98,000–99,000	50
40,500–41,500	50	99,000–118,000	40
41,500–63,000	26	118,000–119,000	50
63,000–66,000	40	119,000–122,000	80
66,000–67,500	50	122,000–124,400	50

5.1. Rotary kiln shell

The thicknesses of the shells along the different sections of the rotary kiln are given in Table 2. In Table 2 zero is placed in the upper end of the rotary kiln, called 'amont'. The distances between supports, in millimeters, are given in Table 3 where 'aval' denotes the lower end of the rotary kiln.

Fig. 2 is a side elevation view of an embodiment of a rotary kiln made in accordance to the present invention, partially showing the interior of the kiln.

Shown in Tables 2, 3 and Fig. 1 is the rotary kiln (1) along with the structural elements to rotate the kilns (3), (12), (8), and (16) around its longitudinal axis. The kiln (1) includes an elongated, cylindrical, rotating shell (13) which has a feed end (9), an opposite discharge end (6), a burner pipe (4). The kiln (1) is erected so that the discharge end (6) is at a lower level then the feed end (9) in order to cause the material (15) being processed. It travels through the open processing zone to the discharge end (6). The kiln shell (13) is supported by riding rings or tyres (3) that engage steel rollers (12) which are supported on concrete piers (5) and steel frames (7).

5.2. Re-injection hole of dust

At a distance of 35 mm from an amont, there are two holes in the rotary kiln wall, designed for the re-injection of dust. They have a rectangular form and a dimension of 0.4 mm length and 0.6 mm in circumference.

5.3. Kiln tyres

The rotary kiln has a strip-rolled sheet per support known as a tyre. Each one is dimensioned with the same inner and outer

Table 3
Distances between supports [8,22].

Supports	Distance (mm)
aval–I	3900
I–II	24,000
II–III	27,500
III–IV	30,000
IV–V	29,500
V–amont	9500

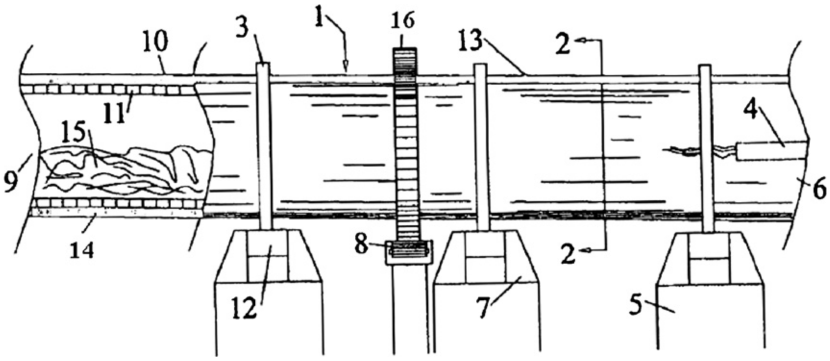

Fig. 1. Thicknesses of the shells along the different sections of the rotary kiln [24].

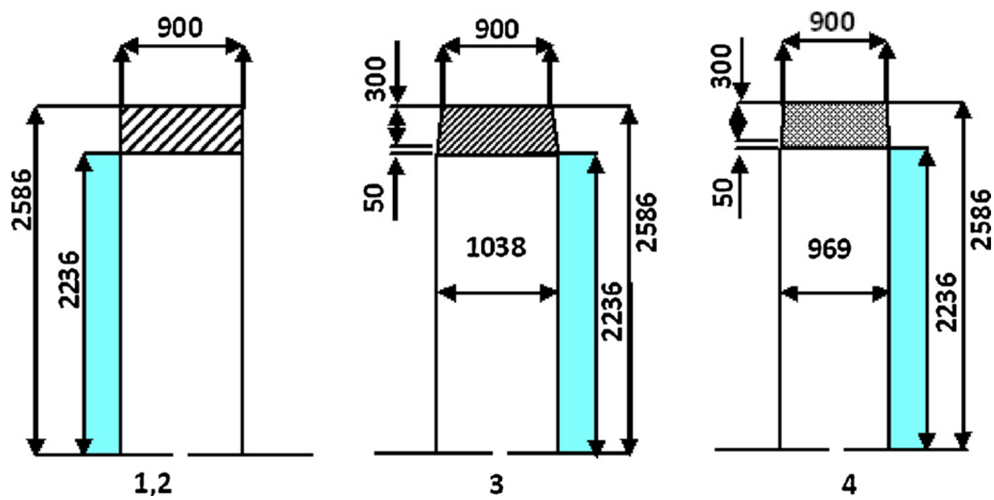

Fig. 2. Sections of kiln tyres [8,22,24].

diameters as well as the same contact length on the support rollers. However, strip sets (3) and (4) vary in design in order to adapt to their interaction with drive components. The different sections of each tyre are shown in Fig. 2.

5.4. Tyre-bearing kiln shell sections

Between the support shell and tyres, there are devices termed tyre-bearing kiln shell sections that perform two main functions:

(1) To allow a gap between the rotary kiln and the tyre, in such a way that contact is adequately maintained.
(2) To limit that gap in order to prevent excessive ovalization of the shell.

5.5. Roller stations

Each tyre is situated on a roller station with a diameter of 1724 mm and each roller station is supported on a concrete foundation. In this model, rollers are situated forming a triangle with the center of the clinker kiln body as shown in Fig. 3 [8,19,25–27].

5.6. Drive components

Since the rotation movement and slope of the kiln body induce longitudinal displacement, the devices called drive components correct this. Only tyres of types (3) and (4) have these drives.

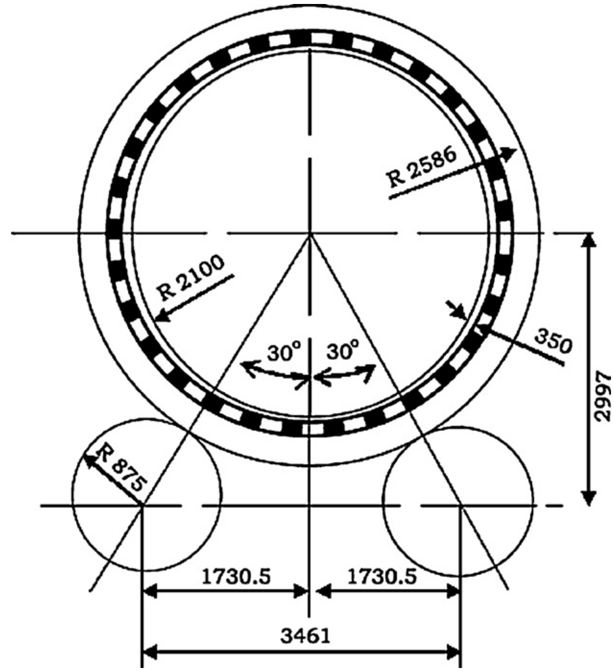

Fig. 3. Geometry part of roller stations [8,22,24,28].

Table 4
Materials used for the kiln [10,29,30].

Component	Material
Shells	AH2CP o HII
Tyres	Cast iron GS-25 Mo.25
Rollers	Cast iron GS-42 Cr Mo.5
Pinion	30 Cr Ni Mo 8 (ISO R 638 = II-68 Type 3)

5.7. Toothed ring and drive pinion

To transmit rotational movement, the kiln has a toothed ring attached to the kiln body. It is fixed to the kiln body through moving links. Rotational velocity is 1.5 rpm/min and mass correspondent to this device is 14,000 kg.

5.8. Materials

Materials used for the kiln are shown in Table 4. These materials are used to build the kiln components. The shell, tyre, roller and pinion are the main components in the kiln. However, the material has been modeled as isotropic and linear, elastic temperature dependent, according to the elastic properties of the steel used in Table 4.

6. Finite element analysis of a reduced model

6.1. Initial approach

A set of reduced models consisting of a body section of the kiln with its corresponding tyre and roller station has been constructed and presented in Fig. 4. The aim of this process was to develop sufficient knowledge regarding contact between shells and tyres and between tyre and rollers. Another important aspect should be considered that this reduced analysis was the convergence process related to finite element mesh refinement [8,10,31].

Different approaches regarding contact boundary conditions and mesh density were investigated by [22]. Normal actions and sliding, with PA, LMM and ALM methods have been included. Some valuable conclusions obtained with this approach are presented below.

6.2. Solid modeling and meshing section

The model has been developed using ANSYS [12–16,32]. Finite elements used are as follows:

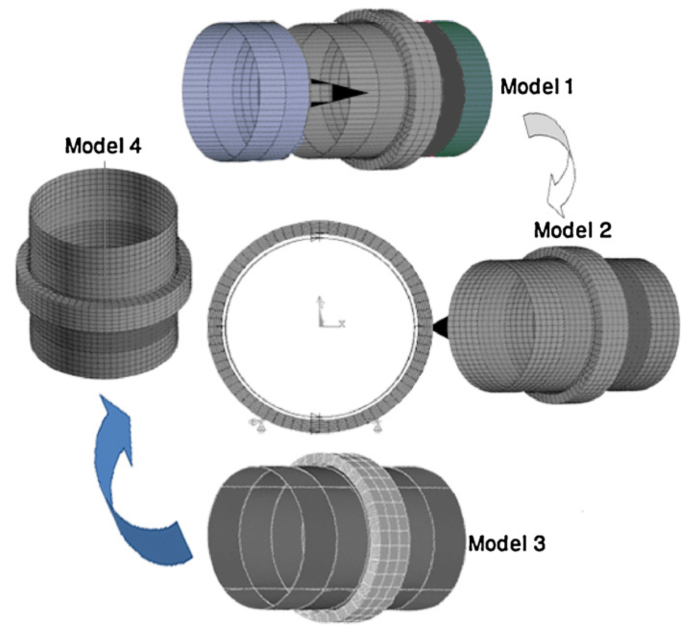

Fig. 4. Reduced models parts [8,10,29,33].

- Shell has eight nodes and double curvature, with six degrees of freedom at each node. This is used to model the rotary kiln shells.
- Solid has 20 nodes with three degrees of freedom at each node, used in the modeling of the bricks for tyres.
- Fig. 5 is a three-dimensional gap of point to point, with three degrees of freedom at each node, with possibility of friction, flexibility, slide and preload. It was employed in the gaps between tyre-bearing and roller stations.
- Fig. 6 is a three-dimensional surface gap, with three degrees of freedom at each node, eight nodes, with the possibility of slide and elastic strain on target elements.
- Fig. 5 represents the surface of strain gap, with their corresponding physical properties. The contact elements are shown in Figs. 5 and 6.

7. Material properties of kiln

The material has been modeled as isotropic and linear, elastic temperature dependent, according to the elastic properties of the steel used in Table 4. Fig. 7a and b shows the variation curves of elastic modulus and thermal expansion coefficient taken from ASME rules [13,22,34,35].

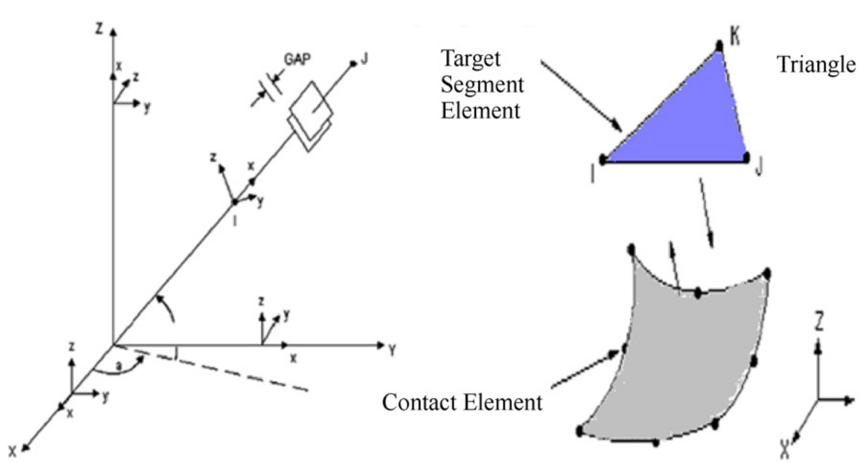

Fig. 5. Vector design of element point-to-point [8,10,24,29,33].

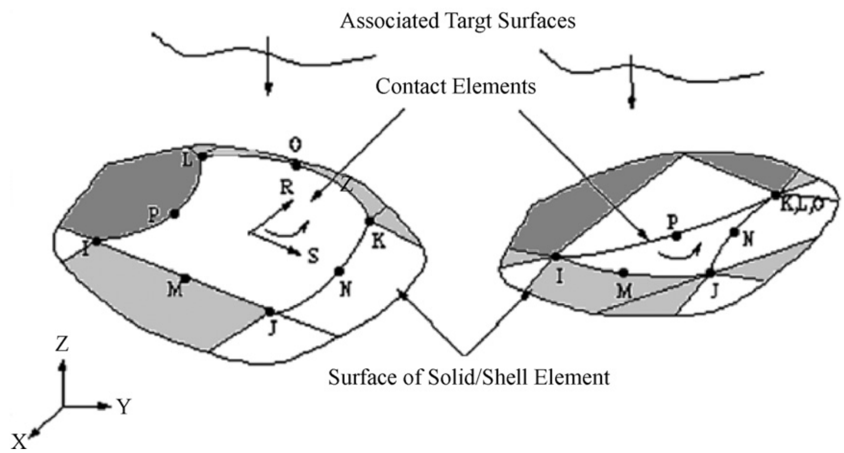

Fig. 6. Element three dimensional surfaces [8,10,24,29,33].

8. Boundary conditions of kiln

The kiln boundary conditions are represented in Fig. 8. Basically, rotations of the kiln have been constrained. In the same way, pairs of nodes corresponding to tyres and kiln body have been coupled in the longitudinal direction and the tyre itself has been constrained in Z direction.

9. Loading analysis and load cases

Loads considered are basically body loads, including refractory bricks and chains, material weight and crust from the clink itself added to the refractory.

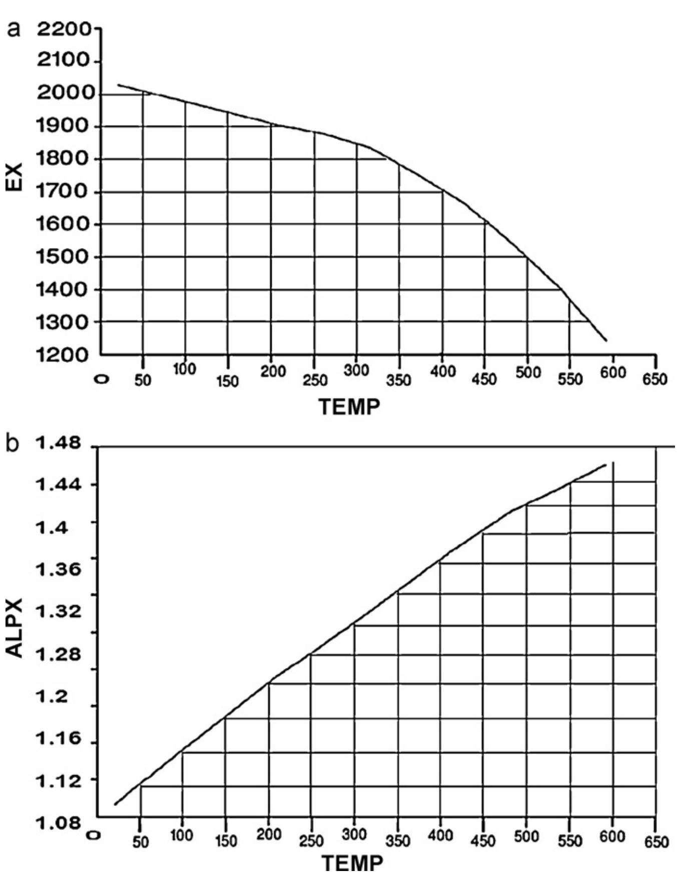

Fig. 7. (a) Elastic modulus and thermal expansion coefficient [8,33]. (b) Elastic modulus and thermal expansion coefficient [8,33].

Since bricks and chains are attached to the shell, mass correspondence to these was modeled as an 'addmass' property of the Shell93 elements. It is a consequence of rotation that clink is dragged with the shell, so that it presents a natural slope of 20°. Consequently, this load condition is modeled in Fig. 9.

10. Finite element measurment

Stresses developed in contact and ovalizations of the kiln body are the primary results we are concerned with. Ovalization is one of the most important aspects in these devices because of its influence on the integrity of the refractories attached to the kiln body. So special care was taken regarding this issue. Tresca failure criteria (stress intensity in ANSYS) were considered in this analysis and ovalization was evaluated from the formula presented below:

$$Ov = \frac{4}{3}(O_D)^2\Delta H \tag{1}$$

$$Ov = 2\frac{Di\ \max - Di\ \min}{Di\ \max + Di\ \min}100 \tag{2}$$

where O_D is the outside diameter and ΔH, Di max, Di min are the radial displacement and the inner diameters, measured at 90° in each section around the shell.

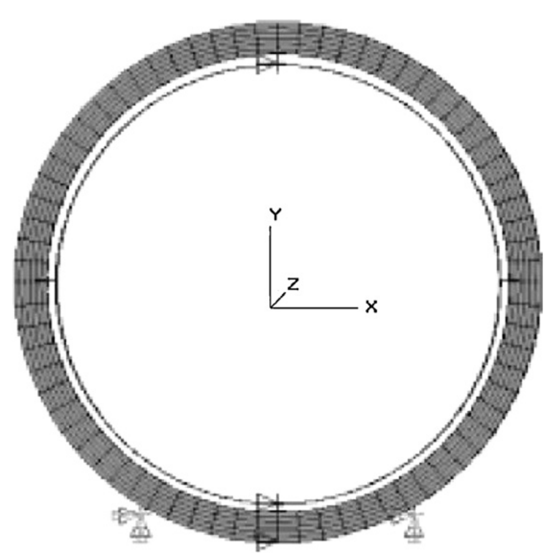

Fig. 8. Boundary conditions of reduced model [35].

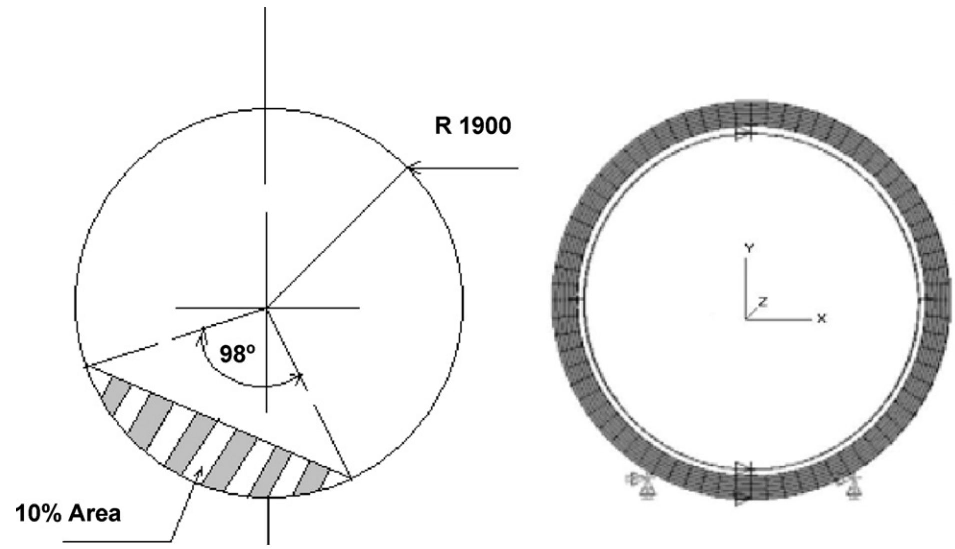

Fig. 9. Load from material weight [35].

The maximum allowable ovalization for the kiln is 10% of the nominal diameter, according to standard rules [12–14,22,36].

11. The wet process and the dry process

The earliest times, two different methods of raw mix preparation were used:

1. The mineral components were either dry-ground to form flour-like powder.
2. A typical water content of 40–45% [37].

Fig. 10 presents the wet process and mean fuel energy used in kilns. The wet process suffered the obvious disadvantage that, a large amount of extra fuel was used in evaporating the water. Furthermore, a larger kiln was needed for a given clinker output, because much of the kiln's length was used up for the drying process. On the other hand, the wet process had a number of advantages. Wet grinding of hard minerals is usually much more efficient than dry grinding.

In 1947 and 1957, the percentage of wet process is near about 63–61. On the contrary, use of fuel energy in kiln was about 6.3–6.1 MJ/kg. However, in 1967–1977, the percentage of wet process went down and at the same time the fuel energy in kiln changes its position. In the dry process, it is very difficult to keep the fine powder raw mix in the kiln because the fast-flowing combustion gases tend to blow it back out again. It became a practice to spray water into dry kilns in order to "damp down" the dry mix, and thus, for many years, there was little difference in efficiency between the two processes and the overwhelming majority of kilns used the wet process. On the other hand, in 1982–2002 the wet process was rapidly down 43–18%. Beside in the same year use the fuel energy in kiln is around 4 MJ/kg [3].

Plants that burn waste fuels enjoy a negative fuel cost. As a result, the inefficiency of the wet process is an advantage to the manufacturer. By locating waste burning operations at older wet process locations, higher fuel consumption actually equates to higher profits for the manufacturer, although it produces greater emission of CO_2.

The average compositions for dried coal and pre-heater exhaust gas are shown in Fig. 11a and b.

Based on the coal composition, the net heat value has been found to be 30,600 kJ/kg coals. The elements found in coal are: hydrogen 5%, oxygen 8.1%, sulfur 2.1%, nitrogen 1.5%, ash 6.9% and water only for 0.4%. The coal composition is very important for cement factory. In many cases, many useful equations are used in composition of cement. Cement is a product obtained by combining a material rich in lime and CaO with other materials. The average composition of Portland cement is shown in Table 5.

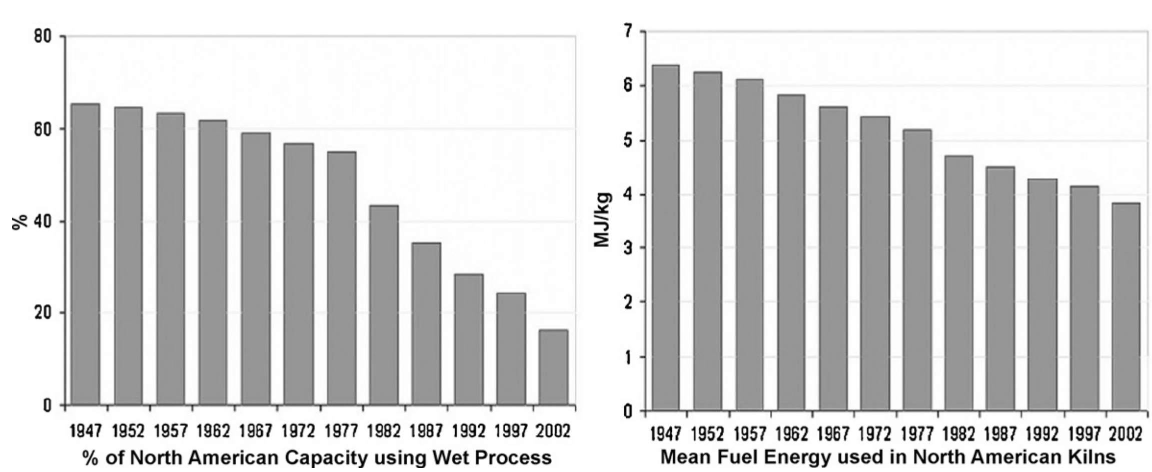

Fig. 10. Wet process and mean fuel energy used in North American kilns [3,38–42].

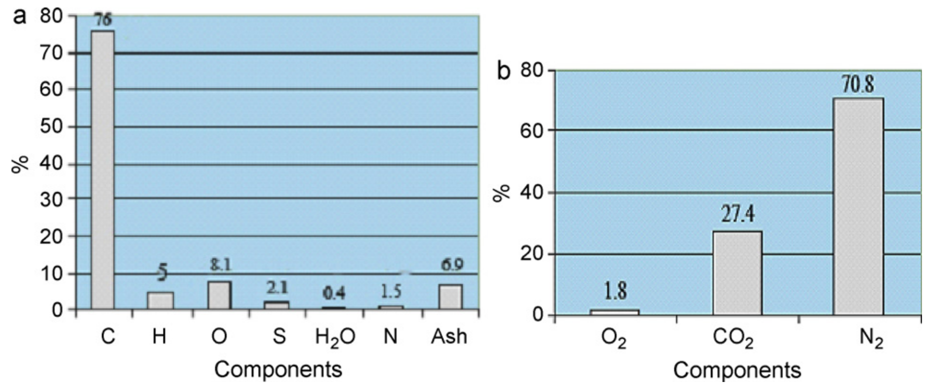

Fig. 11. (a) Coal composition [36]. (b) Pre-heater exhaust gas composition (by weight) [37].

Table 5
Average composition of cement [38].

CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	SO_3	Na_2O	K_2O
50–60%	20–25%	5–10%	2–3%	1–2%	1–2%	1%	1%

Limestone and clay are dug from quarries and crushed separately to fine powders. Crushed limestone and clay mixture fuse and react in strong heat to form cement clinker.

Manufacture of cement (Fig. 12):

Stage 1: Quarry

Mainly limestone and clays as well as other materials containing the required proportions of calcium, silicon, aluminum and iron oxides are extracted using drilling and blasting techniques. In this stage transportation of raw materials from the quarry using trucks and loading or unloading facilities specific to the cement plant are also considered.

Stage 2: Crusher (grinding)

The quarried material is reduced in size by compression and impacted in various mechanical crushers. Crushed rock is reduced in size from 120 cm to between 1.2 and 8 cm and drying of raw material may be necessary for efficient crushing and blending.

Stage 3: Conveyor

Transportation of the crushed material throughout the plant is achieved using some form of powered conveyors.

Stage 4: Mixing bed

The crushed limestone and clay is homogenized by stacking and reclaiming in a long layered stockpile then the material is ready for milling and drying in the kiln.

Stage 5: Raw mill

The raw materials are milled and dried in a roller mill. Heavy rollers are held over a rotating table and the course material is milled until it is fine enough to be carried by air to a homogenizing silo.

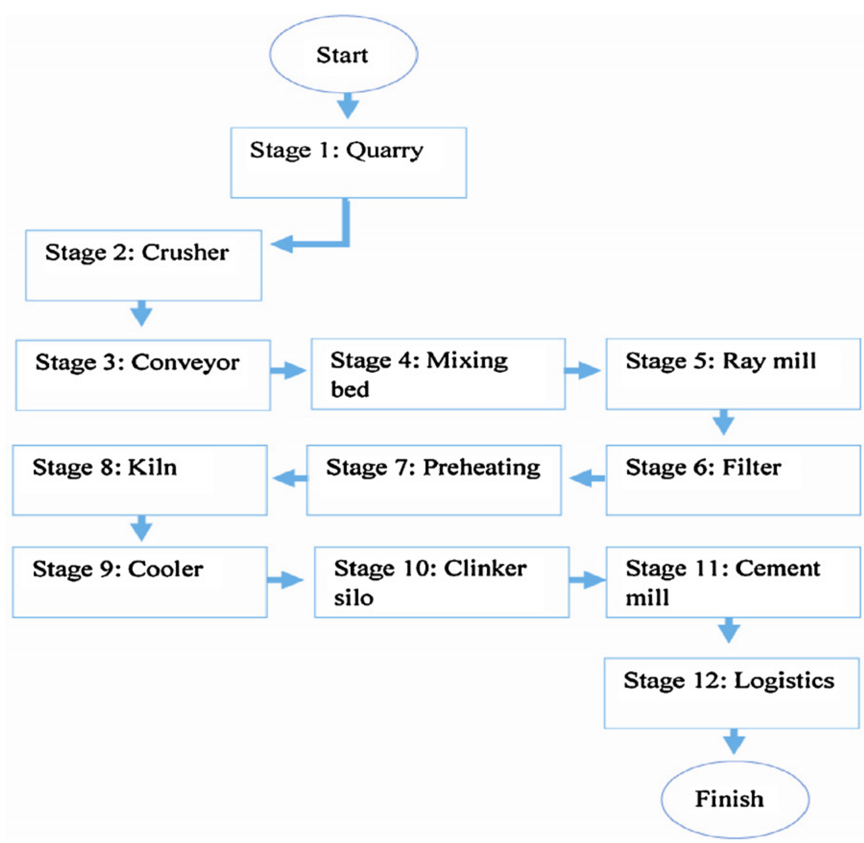

Fig. 12. Stages in cement production flow chart [43].

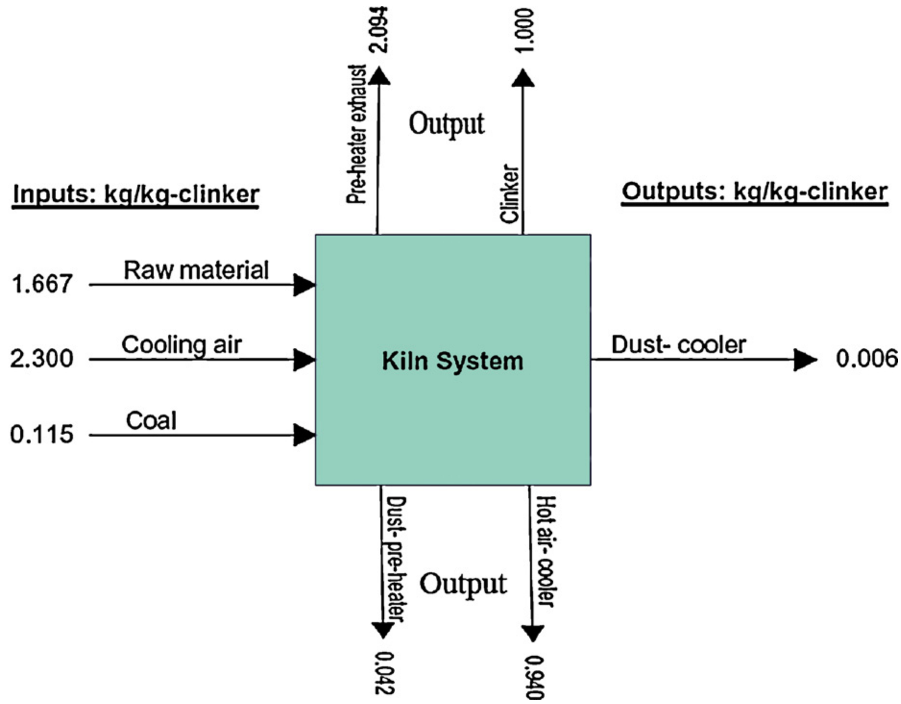

Fig. 13. Mass balance of the kiln system [43].

Stage 6: Filter

Bag filters comprise filters of either woven fabric or needle felts to remove particles from kiln exhaust. The exhaust gas from many kilns is used for drying raw materials, thus improving the energy efficiency of the plant.

Stage 7: Preheating

Cyclone pre-heaters enable the raw material of cement production to be preheated before entering into the kiln. This increases the energy efficiency of the kiln as the material is 20–40% calcined at the point of entry into the kiln.

Stage 8: Kiln

The kiln is designed to maximize the efficiency of heat transfer from fuel burning to the raw material. In the preheated tower, the raw materials are heated rapidly to a temperature of about 1000 °C, where the limestone forms burnt lime. In the rotating kiln, the temperature reaches up to 2000 °C. At this high temperature, minerals fuse together to form predominantly calcium silicate crystals–cement clinker.

Stage 9: Cooler

The molten cement clinker is then cooled as rapid as possible. The ambient air used to cool the clinker is then fed into the kiln as combustion air, ensuring high utilization of the heat produced.

Stage 10: Clinker silo

The clinker may be either stored on site in preparation for grinding to form cement or transported to other sites.

Stage 11: Cement mill

Finish milling is the grinding together of cement clinker, with around 5% of natural or synthetic gypsum.

Stage 12: Logistics

Final cement is stored or transported.

For good quality cement, the ratio:

$$\frac{\%(\mathrm{SiO_2})}{\%(\mathrm{Al_2O_3})} = 2.5,\ 4 \tag{3}$$

$$\frac{\%\,\mathrm{Lime\,(CaO)}}{\Sigma\,\%\,\mathrm{SiO_2, Al_2O_3, Fe_2O_3}} = 1.9,\ 2.1 \tag{4}$$

Chemical reaction in cement manufacture:

$$3CaO + SiO_2 \rightarrow 3CaO{\cdot}SiO_2$$

$$2CaO + SiO_2 \rightarrow 2CaO{\cdot}SiO_2$$

$$2CaO + Al_2O_3 \rightarrow 2CaO{\cdot}Al_2O_3$$

$$4CaO + Al_2O_3 + Fe_2O_3 \rightarrow 4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$$

Fig. 13 shows the clinker input ratio of raw material, cooling air and coal going to kiln system. The feedback ratio, input and output are equal. The input value of raw material, cooling air and coal used are 1.667, 2.300 and 0.115 kg/kg clinker respectively. The average input value is 4.082 kg/kg clinker. On the other hand, the output ratio is divided into five sections. First is the pre-heater exhaust (2.094 kg), second is the clinker (1.000 kg), third is the hot air-cooler (0.940 kg), fourth is the dust-pre-heater (0.042 kg) and fifth is the dust-cooler (0.006 kg). This average is also same to the input value (4.082 kg/kg clinker) but huge amount of clinker is used in pre-heater exhaust section. Only 1.8% used in oxygen, 27.4% in CO_2 and maximum 70.8% of nitrogen are used in pre-heater exhaust. This system is called mass balance of the kiln.

12. Energy saving

Schuer (1992) gave energy consumption values and described the energy saving methods and potentials for German Cement Industry. The study consisted of two parts, namely electrical energy saving methods and thermal energy saving methods. They gave obtained results in the form of energy flow diagrams.

Worrell (2000) performed an in-depth analysis of the US cement industry, identifying carbon dioxide savings, cost-effective energy efficiency measures and potential between 1970 and 1997. They gave the energy efficiency improvement and carbon dioxide emission reductions in the production of cement in the US cement industry. Such large amounts of energy saving need to improve the energy efficiency of combination process. Any success in this

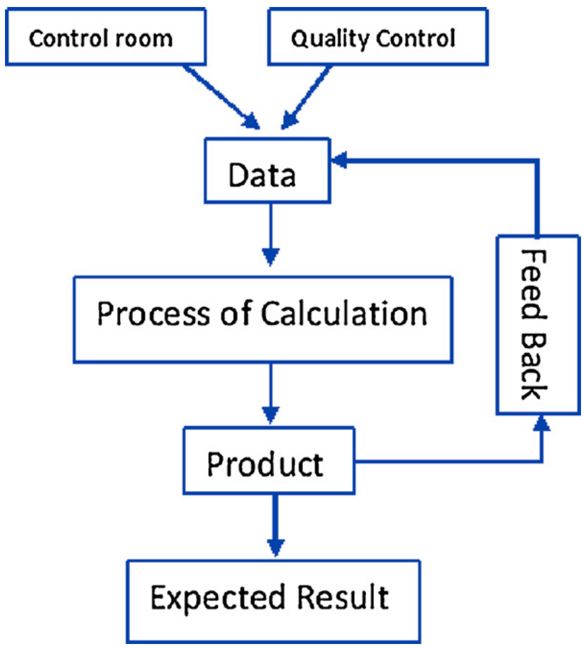

Fig. 14. The rationale of thermal performance analysis [7].

direction, improving machine design and choosing optimal operating and environmental conditions could possibly lead to the development of new approaches toward energy saving in cement production.

A system used in Xinjiang Cement Plant includes a roller-grinding machine, a ball-grinding machine, and a high-efficiency classifier. This system reduced electricity consumption in raw material and finish grinding by 30% and 25%, respectively, compared to the ball mill systems, it replaced.

Roller grinding machines and high-efficiency classifiers are now being produced domestically, at decreased cost. It is estimated that average electricity use for grinding will be reduced about 25% with roller mills and high-efficiency classifiers. This would result in about an 18 kWh reduction per tonne of cement production.

To analyze the potential for reducing energy use and carbon dioxide emissions from cement production in the US, Worrell (2008) compiled information on the costs, energy savings, and carbon dioxide emission reductions of a number of technologies and measures. The technologies and measures fall into two categories: commercially available measures that are currently in use in cement plants worldwide and advanced measures that are either only in limited use or are near to commercialization. Worrell (2008) focuses on retrofit measures using commercially available technologies, but many of these technologies are applicable for new plants as well. For each technology or measurement, we estimate costs and energy savings per tonne of cement produced in 1994. Worrell (2008) then calculate carbon dioxide emission reductions based on the fuels used at the process step to which the technology or measure is applied. Fuel and electricity savings for each efficiency measure were usually calculated as savings per tonne product. To convert savings from a per tonne product basis to a per tonne cement basis we multiplied the savings by the ratio of throughput (production from a specific process) to total cement.

The rationale of the thermal performance analysis of any cement industry, even of any process industry, can be presented through the schematic diagram shown in Fig. 14.

Process industries must introduce a variety of energy saving measures and energy recycling systems to achieve the highest levels of energy efficiency. This can be achieved by incorporating waste energy recovery systems in addition to the industries' comprehensive technological capabilities. It is to be noted that the energy savings up to 20% can be achieved by incorporating appropriate waste energy recovery systems [44,45].

Table 6
Comparative thermal energy consumption of different kiln technologies [38].

Kiln type	Additional information	Energy intensity (MJ/tonne clinker)
New dry	Best performance (large)	2950
	Average (large and medium)	3300
	Without precalciner (small)	4000
Long	Wet process	5000–6700
	Dry process	5000
Lepol		3300–5200
Shaft		3100–6500
Dry hollow		6270–8360

The development of recycling and energy recovery systems in industry is thus important and required to replace the conventional industrial processes with a continuous and sustainable structure. This development has been implemented in some of the developed countries to save energy consumption as well as to control their industrial pollution. However, this approach is not fully been introduced or implemented yet in the developing countries despite its great need to save energy as well as to control their industrial (environmental) pollution [46,47].

12.1. Process kilns energy efficiency

The kiln is the essential part of a cement plant. It is a huge furnace where the cement clinker is made. It is supplied by the raw mix and energy delivered in the form of an intense flame. The flame temperature is above 1850 °C. The efficiency of a kiln is mainly determined by the design of the process. Different kiln technologies exist and have different levels of performance. A kiln has a typical lifetime of 50 years. A large number of kilns in operation were built decades. As a result, the present average kiln efficiency level in a country is not representative of current worldwide best practices; rather, it reflects a country's industrial and technological history [47–49]. A set of international best practices and best efficiencies is now largely shared worldwide through the presence of global companies in the field of plant engineering and cement production. Fig. 6 represents a number of different cement kiln technologies available and provides a comparison of their thermal energy consumption in MJ/tonne clinker. Under most circumstances new large dry kilns are the most efficient option, consuming an average of 2950 MJ heat energy per tonne of clinker. For the time being the best possible energy efficiency is at around 2700 MJ/tonne clinker (Table 6).

The size of the kiln plays a vital role and larger kilns like the once producing 5000 tpd (tonnes/day) are more efficient. Not surprisingly, there are limits to the size of the kiln:

- Modern kilns have a diameter of 6 m and length up to 100 m. Any larger kiln would bend too much under its own weight leading to cracks in the brittle refractory material.
- Transportation of raw materials and to markets is another limit: therefore, the choice of site is very important. Small kilns are only justified in small and remote local markets (e.g., Himalayan areas) where transportation is difficult and the population density is low.

Use of the most modern kiln technology represents an obvious choice to reduce the energy required by the process. This clearly stresses the need for the adoption of the best possible new dry kilns of large size equipped with preheaters and precalciners. A failure to do so by adopting less advanced technologies increases the environmental pollution, releases more greenhouse gases and is much more energy intensive [50,51]. In turn the related cost over the

Table 7
Capital costs and cost effectiveness of NO_x control technologies [55,56].

	Kiln type	Kiln capacity (tonnes/clinker/h)	Capital costs (103$)	NO_x removed (tonnes/year)	Cost effectiveness ($/tonne NO_x removed)
Low NO_x burner	Long wet	30	1640	290	1130
	Long wet	50	2180	480	880
	Long dry	25	1270	210	1270
	Long dry	40	1640	340	970
	Preheater	40	1490	230	1330
	Preheater	70	2040	410	970
	Precalciner	100	1720	340	1010
	Precalciner	150	2170	510	830
Mid-kiln	Long wet	30	718	590	550
	Long wet	50	748	480	450
	Long dry	25	708	210	610
	Long dry	40	728	340	470
	Preheater	40	N/A	N/A	N/A
	Preheater	70	N/A	N/A	N/A
	Precalciner	100	N/A	N/A	N/A
	Precalciner	150	N/A	N/A	N/A
SNCR urea-based	Long wet	30	N/A	N/A	N/A
	Long wet	50	N/A	N/A	N/A
	Long dry	25	N/A	N/A	N/A
	Long dry	40	N/A	N/A	N/A
	Preheater	40	671	470	930
	Preheater	70	927	825	790
	Precalciner	100	969	680	880
	Precalciner	150	1240	1,020	800
SNCR ammonia-based	Long wet	30	N/A	N/A	N/A
	Long wet	50	N/A	N/A	N/A
	Long dry	25	N/A	N/A	N/A
	Long dry	40	N/A	N/A	N/A
	Preheater	40	1340	470	1100
	Preheater	70	1850	925	910
	Precalciner	100	1650	680	980
	Precalciner	150	2110	1020	880
	Long wet	30	12.8*	930	3600
SCR	Long wet	50	17.4*	1550	3140
	Long dry	25	9.87*	690	3630
	Long dry	40	13.11*	1100	3170
	Preheater	40	12.0*	750	4120
	Preheater	70	16.8*	1320	3490
	Precalciner	100	19.3*	1090	4870
	Precalciner	150	24.6*	1630	4400

complete plant lifetime will by far exceed the short term reduction of investment costs for a cheaper plant. Nevertheless, not all kilns built recently will reach optimal performance. This is often due to the use of lower-cost domestically produced technologies. The case of refractory materials used to realize the thermal insulation of the kiln perfectly illustrates this problem. Upgrading to a state of the art refractory material can save up to 500 MJ/tonne clinker. Compared to foreign companies, developing countries like China often have less efficient refractory materials. Therefore, industrial cooperation in every possible form should be encouraged and the upgrade to a more efficient material systematically done, since it can be funded by emission reduction projects. Banning the construction of low efficiency kilns is one of the easiest solutions. This can be achieved through permitting procedures or setting minimum standards [52].

13. Cost of kiln using nitric oxide (NO)

The US cement industry uses the nation's 213 cement kilns to produce about 81 million tonnes of cement a year. Nearly all NO, emissions from cement manufacturing are the result of the high process temperatures out of these kilns. Among the states, California, Texas, Pennsylvania, Michigan, Missouri and Alabama are the top cement producers. All of these states have capacities greater than 4 million tonnes. There are four basic kiln types, which together emit an estimated 118,000–146,000 tonnes of NO, annually. Emission factors, on average, range from 3.4 to 9.7 lbs NO/tonne of product, depending on the type of kiln and site-specific factors [53–55].

Number of NO control strategies is available with reduction efficiencies ranging from 20 to 90%. At a typical kiln, these controls can achieve NO reductions of hundreds of tonnes a year, compared to uncontrolled NO levels. EPA estimates of cost effectiveness ($/tonne of NO_x removed) range from $830–1330 for low NO burners to $450–610 for mid-kiln firing, to $790–930 for urea based SNCR to $3140–4870 for SCR [56,57] (Table 7).

13.1. Costs and cost effectiveness

One SNCR vendor estimates that the capital cost including equipment, engineering, installation, license fee, service contract, start-up, optimization and training of applying the technology to a cement kiln, based on a demonstration in late 1993, would be a consistent $0.08/tonne on a 15-year life, 85% average plant capacity of 100 tonnes/h normal output. This SNCR vendor also estimated the operating costs, which are a direct function of the firing rate in the kiln necessary to process the raw material mix. Raw material variations change the firing rate and NO_x levels are either below the permit level, where no chemical is required, or above where the chemical rate will be needed to lower the NO_x emissions to below the permit level.

To maintain NO, emissions at 400 lb/h, the operating cost of the SNCR system on the subject kiln was estimated at $0.14/tonne. As shown in Table 8, EPA's 1994 draught ACT document estimates the

Table 8
US clinker capacities by state, rank1 [21,54,55,62].

State	Clinker (10^3 tonnes)
California	10,390
Texas	8590
Pennsylvania	6640
Michigan	4900
Missouri	4680
Alabama	4260
Florida	3360
New York	3100
Indiana	2830
Iowa	2810
Illinois	2590
South Carolina	2580
Kansas	1890
Oklahoma	1890
Maryland	1860
Colorado	1800
Arizona	1770
Ohio	1700
Georgia	1380
Arkansas	1310
Virginia	1120
Tennessee	1050
Nebraska	960
Utah	930
West Virginia	820
South Dakota	770
Kentucky	720
Montana	590
Mississppi	500
Oregon	500
New Mexico	490
Washington	470
Wyoming	460
Maine	460
Nevada	420
Hawaii	260
Idaho	210
Total	81,060

total capital costs and cost effectiveness of several control technologies for eight model plants. As indicated, cost effectiveness ($/tonne of NO, removed) ranges from $830–$1330 for low NO_x burners, to $450–610 for mid-kiln firing, to $790–930 for urea based SNCR, to $3140–4870 for SCR. For each kiln type, the cost effectiveness of each control strategy varies inversely with kiln capacity. In 1991, the SCAQMD estimated the cost effectiveness of using SCR to reduce cement kiln NO_x emissions by 85% to be $1300/tonne of NO_x reduced [40,53,58,59].

The recent data show a total of 213 cement kilns at approximately 100 plants in the US, producing about 81 million tonnes of Portland cement a year. The industry's annual clinker capacity has steadily declined from the 1973 peak of 414 kilns with a capacity of 91 million tonnes (clinker production is being exported). Table 8 profiles the clinker-producing capacity in the US by state. California, Texas, Pennsylvania, Michigan, Missouri, and Alabama all have clinker capacities greater than 4 million tonnes [60,61].

14. Kiln control

The main objective of kiln operation is to make clinker with the combined chemical and physical properties. The maximum rate and the size of kiln will be allowed in the system. Whilst the system environmental meeting standards at the lowest possible operating cost, the kiln is very sensitive to control strategies and poorly run kilns can easily double the cement plant operating costs.

Formation of the desired clinker minerals involves heating the raw mix through the temperature stages mentioned above (11). After the finishing, transformation takes place in the hottest part of the kiln, under the flame, is the reaction of calcium sulfate (Ca_2SiO_4) with calcium oxide to form $Ca_3O{\cdot}SiO_4$:

$$Ca_2SiO_4 + CaO \rightarrow Ca_3SiO_5 \quad (5)$$

Also abbreviated in the cement chemist notation (CCN) as:

$$C_2S + C \rightarrow C_3S \quad (6)$$

The tricalcium silicate is thermodynamically unstable below 1250 °C but it can be preserved in a met stable state at room temperature by fast cooling. On slow cooling it can tend to revert to calcium sulfate (Ca_2SiO_4) and calcium oxide (CaO). If the reaction is incomplete, excessive amounts of free calcium oxide remain in the clinker. Regular measurement of the free CaO content is used as a means of tracking the clinker quality. As a parameter in kiln control, free CaO data is ineffective. Because even with fast automated sampling and analysis of the data, when it arrives, may be 10 min out of date and more immediate data must be used for minute-to-minute control.

Conversion of calcium sulfate to calcium oxide requires partial melting. The resulting liquid being the solvent in which the reaction takes place. The amount of liquid and their speed of the finishing reaction, are elated to temperature. To meet the clinker quality object, the most obvious control is that the clinker should reach a peak temperature such that the finishing reaction takes place to the required degree. A further reason to maintain constant liquid formation in the hot end of the kiln is that the sintering material forms. A dam prevents the cooler upstream feed from flooding out of the kiln. The feed in the calcining zone, is a powder evolving carbon dioxide, is extremely liquid. Cooling of the burning zone and loss of unburned material into the cooler is called "flushing" and in addition to causing lost production can cause massive damage.

However, for active operation, steady conditions need to be maintained throughout the whole kiln system. The feed at each stage must be at a temperature such that it is ready for processing in the next stage. To maintain this, the temperature of both feed and gas must be identified and maintained at every point. The external controls available to achieve this are few points:

- *Feed rate*: This defines the kiln output.
- *Kiln speed*: This controls the rate at which the feed moves through the kiln tube.
- *Fuel injection rate*: This controls the rate at which the "hot end" of the system is heated.
- *Exhaust fan speed or power*: This controls gas flow and the rate at which heat is drawn from the "hot end" of the system to the "cold end".

In the case of precalciner kilns, further controls are available:

- Independent control of fuel to kiln and calciner.
- Independent fan controls where there are multiple preheated strings.

The independent use of fan speed and fuel rate is constrained by the fact that there must always be sufficient oxygen available to burn the fuel. In particular, carbon is burned to carbon dioxide. If carbon dioxide is changed then the carbon monoxide is formed, this represents a waste of fuel and also indicates reducing conditions within the kiln which must be avoided at all costs since it causes destruction of the clinker mineral structure. For this reason, the exhaust gas is continually analyzed for O_2, CO, NO and SO_2.

There are many different types of kiln controllers. Some can control the atmosphere of the kiln as well as the temperature. There are two types of programs that can be entered into the controller. One is custom designed programs (Table 9) and second are programs

Table 9
Custom designed programs [53].

Segment	Rate (°C % h)	Ending temperature (°C)	Hold
1	10	65.55	24:00
2	65.55	537.77	4:00
3	4.44	621.11	0
4	298.88	1148.88	0
5	42.22	1285	0

which come with the controllers that are designed to simulate a firing, using cones. These are commonly called Cone Fire programs.

The calculation of amount to be paid off, the clinker peak temperature has always been difficult to understand. Contact temperature measurement is impossible because of the chemically aggressive and abrasive nature of the hot clinker and optical methods such as infrared pyrometry are difficult because of the dust and fume-laden atmosphere in the burning zone. The traditional method of assessment was to view the bed of clinker and deduce the amount of liquid formation by experience. As more liquid forms, the clinker becomes stickier. The bed of material climbs higher up the rising side of the kiln. It is usually also possible to assess the length of the zone of liquid formation, beyond which powdery fresh feed can be seen. The formation of NO from nitrogen and oxygen takes place only at high temperatures. Therefore, the NO level gives an indication of the combined feed and flame temperature. The sulfur dioxide (SO_2) is formed by thermal decomposition of calcium sulfate in the clinker and it gives an indication of clinker temperature. Modern computer control systems usually make a calculated temperature using contributions from all these information sources and then set about controlling it.

15. Clinker cooling control

The clinker cooling operation recovers up to 30% of kiln system heat. Preserves the ideal product qualities and enables the cooled clinker to be avoided by conveyors. The most common types of clinker coolers are reciprocating grate, planetary and rotary. Air sent through the clinker to cool it, is directed to the kiln where it nourishes fuel combustion. The fairly coarse dust collected from clinker coolers is comprised of cement minerals and is restored to the operation. Based on the cooling efficiency and desired cooled temperature, the amount of air used in this cooling process is approximately 1–2 kg/kg of clinker. The amount of gas to be cleaned following the cooling process is decreased when a portion of the gas is used for other processes such as coal drying.

16. Conclusion

Cement kiln is used for calcining cement clinker and it can be used widely for cement, metallurgical, chemical industries, etc. The common kiln is composed of the shell, the supporting device, the supporting device with thrust roller, the driving device, the movable kiln head, the sealing device at kiln tail, the combustion device, and so on. It has the simple structure and reliable operation and at the same time, the production process of the kiln can be controlled easily. This study briefly provided an overview of kiln system, construction, production, design, materials and so on. In this part of kiln modeling and loading arrangement, the kiln loading based on its kiln thickness. However, the geometric model also provides an overview of the rotary kiln system, kiln shell, tyre, roller and so on. Here material properties, boundary conditions, loading and load cases in the kiln system are discussed as well. It was found that a larger kiln was needed for a given clinker output because much of the kiln's length was used up for the drying process. On the other hand, the wet process had a number of advantages. Wet grinding of hard minerals is usually much more efficient than dry grinding. A large number of kilns in operation were built few decades ago. As a result, the present average kiln efficiency level in a country is not representative of current worldwide best practices. Kiln control is one of the most vital parts in the cement production. The kiln is very sensitive to control strategies and poorly run kiln can easily double the cement plant operating. The clinker cooling is also included in the part of this control. The most common types of clinker coolers are reciprocating grate, planetary and rotary. Finally, cost of nitric oxides and there cost effectiveness data on control technologies were discussed.

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